VIBRATION DAMPING OF THE CASSINI SPACECRAFT STRUCTURE

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BIOGRAPHY

Them Bergen earned a B.S. in Mechanical Engineering from The University of Texas at Austin and an M.S. in Acoustics from The Pennsylvania State University. He has been employed for the last four years in the Dynamics Environments Engineering Group at JPL where he has worked to assess and mitigate various noise and vibration problems with analysis and test on several spacecraft projects.

ABSTRACT

Cassini is a large robotic spacecraft currently under development at the Jet Propulsion Laboratory (JPL) whose interplanetary scientific mission is to explore Saturn, its rings, and its moons. Cassini is scheduled to launch on a Titan IV rocket with a Centaur upper stage booster, and will be protected during ascent through the atmosphere by a lightweight aluminum payload fairing (PLF). As a result of the extreme noise levels generated by the powerful Titan IV at liftoff, and the acoustic transparency of the PLF, Cassini is predicted to experience severe acoustic levels. Furthermore, the high acoustic levels, coupled with the size and configuration of the spacecraft, will induce unacceptable random vibration levels on the structure and critical spacecraft components. Studies showed that the use of Tuned Vibration Absorbers (TVAS) would be effective in reducing vibration. A series of reverberant acoustic tests were performed on a partial development test model (DTM) of Cassini to evaluate the effectiveness of TVAS in reducing the structural vibration. The test results showed that significant vibration attenuation was achieved.

KEYWORDS: Cassini spacecraft, Titan IV payload fairing, damping, viscoelastic material, tuned vibration absorber, vibration reduction, reverberant acoustic test

1NTROD1JCTION

Cassini is a robotic spacecraft currently under development at the Jet Propulsion Laboratory (JPL) whose interplanetary scientific mission is to explore Saturn, its rings, and its moons in the early 21st century. Cassini (Figure 1), the largest spacecraft ever assembled at JPL, is scheduled to launch in October 1997 from Kennedy Space

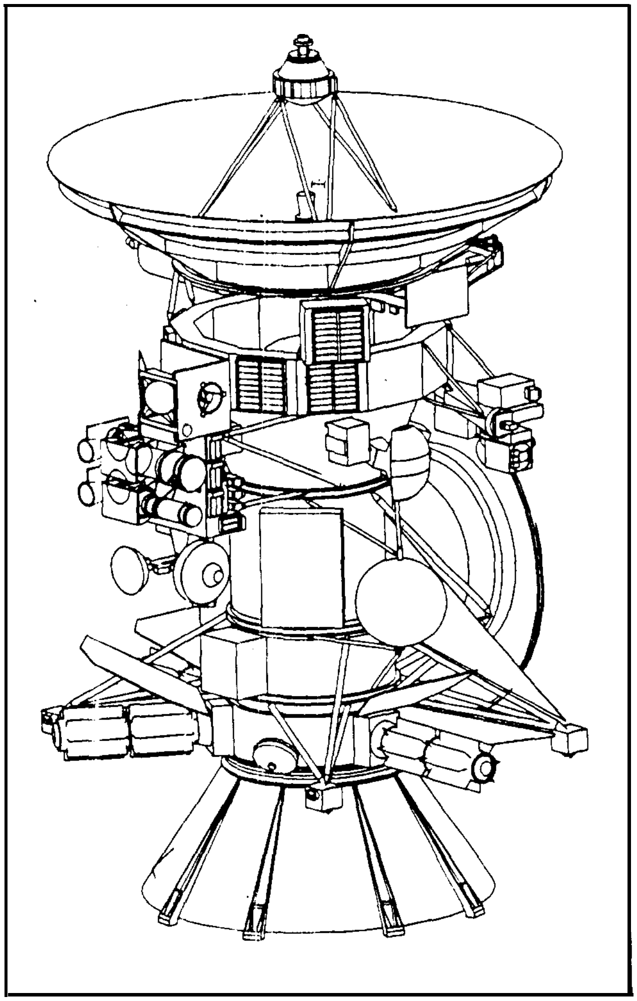


Figure 1: The Cassini Spacecraft Launch Configuration.

Center (Cape Canaveral, FL) on board a Titan] V launch vehicle with a Centaur upper stage booster which arc provided by Martin Marietta (Denver,CO). I'hc spacecraft is 7.0 m (22.8 ft) high and the diameter of the core structure is 1.3 m (4,2 ft). Cassini will be protected during ascent through the atmosphere by a lightweight aluminum 66-foot payload fairing (PLF) which is provided by McDonnell Douglas (Huntington Beach, CA). The Cassini/Centaur/Titan IV PLF launch configuration is illustrated in Figure 2.

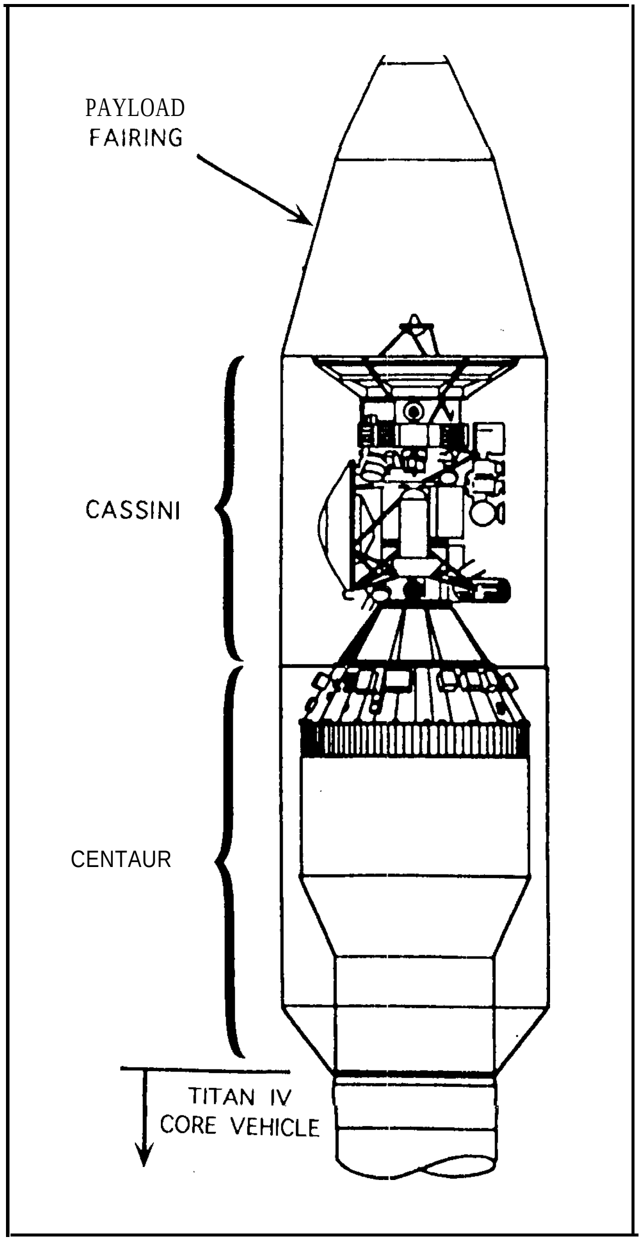


Figure 2: The Cassini/Centaur/Titan IV Payload Fairing Launch Configuration.

As a result of the extreme noise levels generated by the powerful Titan IV at liftoff, and the acoustic transparency of" the PLF, Cassini is predicted to experience severe acoustic levels. The Cassini acoustic test criteria levels were derived from Titan IV flight data recorded during launches from Cape Canaveral (see Reference 1). The test levels (143 dB overall for Flight Acceptance) arc plotted in Figure 3 and compared with the flight data statistics, The high acoustic levels, combined with the size and configuration of' the spacecraft, will induce unacceptable random vibration levels on the structure and critical attached hardware components. Efforts to mitigate the vibroacoustic environment by modifying the spacecraft structure were investigated. Preliminary analyses showed that the use of Tuned Vibration Absorbers (TVAs) would be effective in controlling vibration. In this paper, the operating principles, design, and installation of the TVAs are described, an acoustic test program to characterize TVA performance is outlined, anti test results arc presented which show that significant vibration attenuation was achieved with minimum impact to the spacecraft development

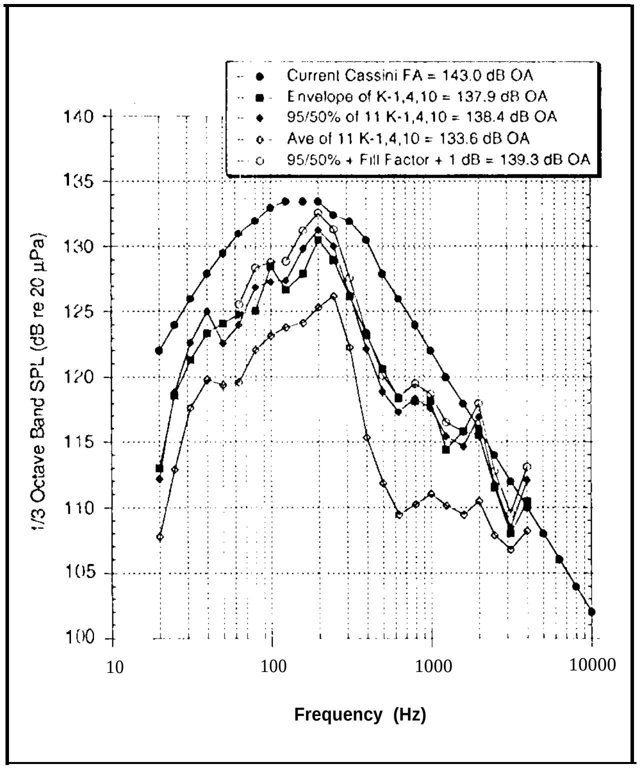


Figure 3: Cassini Flight Acceptance Acoustic Test Criteria Levels Compared With Adjusted Flight Data Statistics.

SPACECRAFT MODIFICATION FEASIBILITY STUDY

An analytical study of vibration reduction techniques fOr the Cassini launch vibration environment was performed at JPL. The objective o! this feasibility study was to identify potential practical modifications to the spacecraft structure to attenuate the acoustically excited vibration. Since the structural design of Cassini was fairly mature at the initiation of the study, efforts were focused on "add-on" modifications rather than a major redesign. It was established that the desired reduction should be achieved around 200-250 Hz since that is the frequency range in which the acoustic spectrum peaks, and where ring modes of the Cassini core structure occur, as well as modes of some of the attached hardware components. Preliminary studies indicated that a structural damping treatment using viscoelastic materials (VEMs) represented a viable technique of reducing vibration with minimum impact to weight, cost, and redesign. Additional modifications were considered, but were eliminated due to technical imitations.

Initially, constrained-layer damping, (CLD) of the spacecraft skin structures appeared to be an attractive solution. However, closer examination of CLD showed that such a treatment would only be effective wel i above the frequency range of interest where panel modes occur on the structure (>500 Hz). JPL consulted with engineers at Roush Anatrol, inc. (Cincinnati, OH), who suggested that the use of Tuned Vibration Absorbers (l'VAs) would be effective in suppressing the ring mode vibration of the primary structure, and, subsequently, sensitive attached hardware. TVAs are single degree-of-freedom clamped mechanical oscillates which act as dynamic absorbers.

Roush Anatrol, Inc. was hire.d to examine methods of damping the spacecraft vibration using viscoelastic materials (VEM). A detailed finite element model (FEM) of the lower sections of the Cassini primary structure was developed at JPL for an acoustic sensitivity analysis. Acoustic forcing functions for the FEM were derived from a boundary element model (BEM) of the partial structure in the JPL acoustic test chamber. Roush Anatrol engineers exercised the model with several different TVA configurations by varying locations, masses, damping, tuning, and number of TVAS. Their preliminary sensitivity analyses examining TVAS indicated that significant reduction was achievable by distributing several TVAs around the ring frames of the structure. Subsequently, Roush Anatrol was asked to design the TVAs and select the appropriate VEMs with consideration of outgassing and thermal requirements.

TUNED VIBRATION ABSORBERS

TVAs are compact single degree-oi'-freedom mechanical oscillators, in which a VEM serves as the spring and damping element. TVAs work best at controlling single-mode structural vibration, however, it has been shown that a properly tuned TVA with the appropriate VEM can provide broadband attenuation. A TVA attached to a structure, and tuned to the same frequency of oscillation as the structural mode of concern, will split the mode into two with an antiresonance in between (like a two degree-of-freedom system) as shown in Figure 4. In addition, a high level of damping in the VEM can lower the resonance peaks, anti raise the antiresonance valley, (as shown by the dashed curve in Figure 4) to provide an overall reduction in vibration around the two modes. Since the resonance of the T\ 'As must be strongly excited by motion of the base structure for the greatest effect, it is best to locate the TVAS away from nodes on the structure. A detailed treatise on discrete damping devices, including TVAS, is provided in Reference ?.

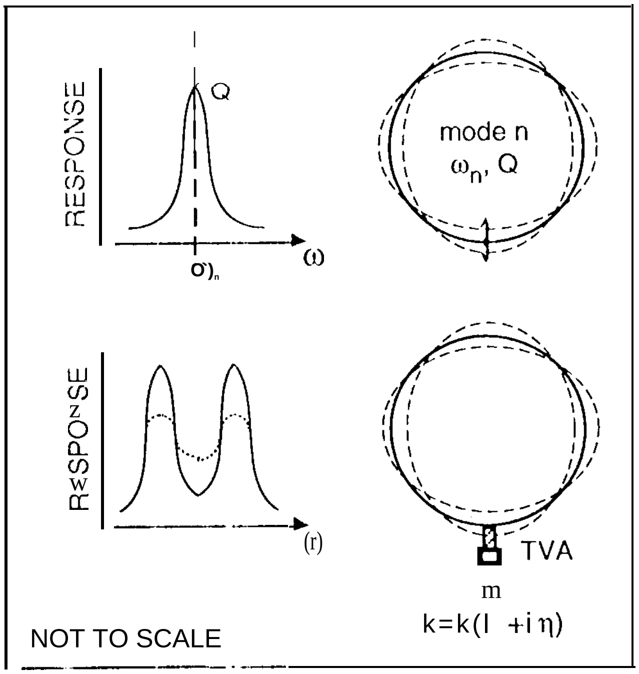
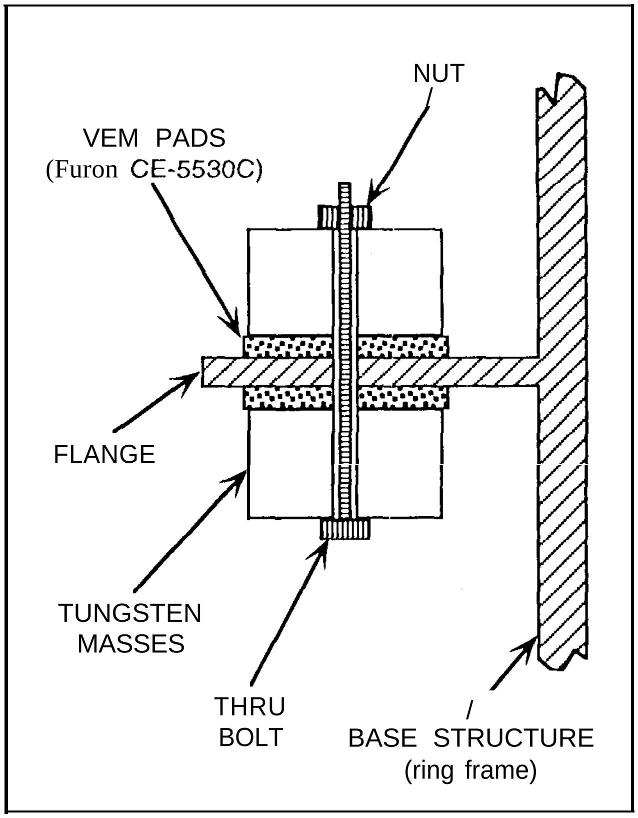


Figure 4: Operating Principle of Tuned Vibration Absorbers Applied to Single Mode of Ring Structure.

A schematic of a TVA similar to [hose used on Cassini is given in Figure 5. Generally, the design of TVAs varies, and depends greatly on the application. The unit consist basically of a rigid mass bolted onto the structure through the VEM pad. In the case of Cassini, 1.36 kg (3.0 lb) Tungsten masses were used, and the VEM selected by

Roush Anatrol was Furon CE-5530C. Tbc tungsten was alloyed with copper and nickel so that it was non-magnetic, and the Furon VEM was chosen because it possessed a high damping loss factor with low sensitivity to temperature, and negligible outgassing characteristics. The TVAS for Cassini were designed to reduce the acoustically excited radial vibration of the ring frames by exciting the shear mode of the TVAs.



'igure 5: Tuned Vibration Absorber Configuration Designed to Operate in Shear Mode.

The TVAS arc tuned simply by adjusting the torque on the nut which changes the spring rate of the VEM. Small accelerometers arc located on the TVA mass and base structure whose signals arc input to a dual channel spectrum analyzer. The tuning frequency is determined by exciting the system while observing the transmissibility (mass response/hasc response) of the TVA on the analyzer.

Roush Anatrol analytically showed that 3-10 dB reduction in vibration around 200 Hz was achievable by distributing a total of sixteen (16) TVAs on the major ring frames of the Cassini structure. in response to the encouraging preliminary results, acoustic testing of a partial Cassini structure was included in the development test schedule to evaluate the effectiveness of the vibration reduction prototype hardware which would be fabricated and delivered and tuned by Roush Anatrol.

ACOUSTIC TEST PROGRAM

Available Cassini hardware was assembled for acoustic testing to assess the vibroacoustic environment and the 'f 'VA performance. The test object, called the Partial Development Test Model (DTM), included both flight and mock-up structure. An outline of the test objectives and description of the test configuration is provided.

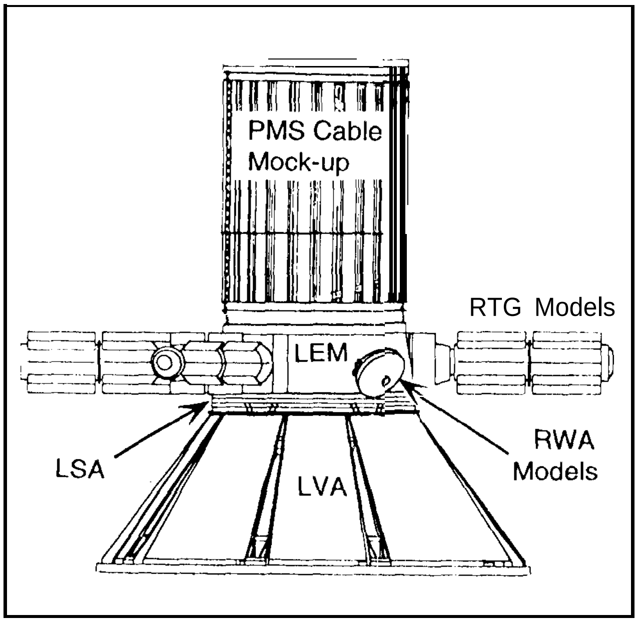
Test Objectives

The test objectives were defined for Cassini dynamics environments evaluation, and were listed as follows: (1) evaluate the effectiveness of the prototype TVAS provided by Roush Anatrol, (2) evaluate the launch random vibration environments for attached spacecraft assemblies such as for the Reaction Wheel Assemblies (RWAs), the Radioisotope Thermoelectric Generators (RTGs), and the Main Engine Assembly (MEA), (3) directly measure interface forces for the RTGs and MEA, and (4) obtain vibration measurements for correlation with analytical models. With the test objectives in mind, the test article was appropriately instrumented with accelerometers on the primary structure and attached hardware, force transducers at the RIG and MEA attachment points, and microphones.

Test Configuration

A schematic of the Cassini Partial-DTM test article is given in Figure 6. The following hardware items were available for the acoustic tests: the flight Launch Vehicle Adapter (I .VA), the DTM Linear Separation Assembly (LSA), the flight Lower Equipment Module (LEM) with RTG and RWA support structures, three (3) RTG models (two mass models, one dynamic simulator), three (3) RWA mass mock-ups, the Propulsion Module Subsystem (l'MS) structure cable mock-up, the MEA mock-up provided by Martin Marietta (Denver, CO), and the TVA hardware provided by Roush Anatrol.

The '1 VAS were installed on the LEM and LVA forward rings as shown in Figure 7. Special brackets were fabricated and fastened to the LEM forward ring so that the TVAs could be mounted in the correct orientation to reduce radial ring motion. The TVAs were located around the circumference of the rings as shown in Figure 8. These locations were selected primarily because they did not interfere with space constraints, and provided a somewhat uniform distribution around the rings. A total of 16 TVAS were installed, All TVAs were tuned to around 200117. by Roush Anatrol engineers.



igure 6: The Cassini Partial Development Test Model.

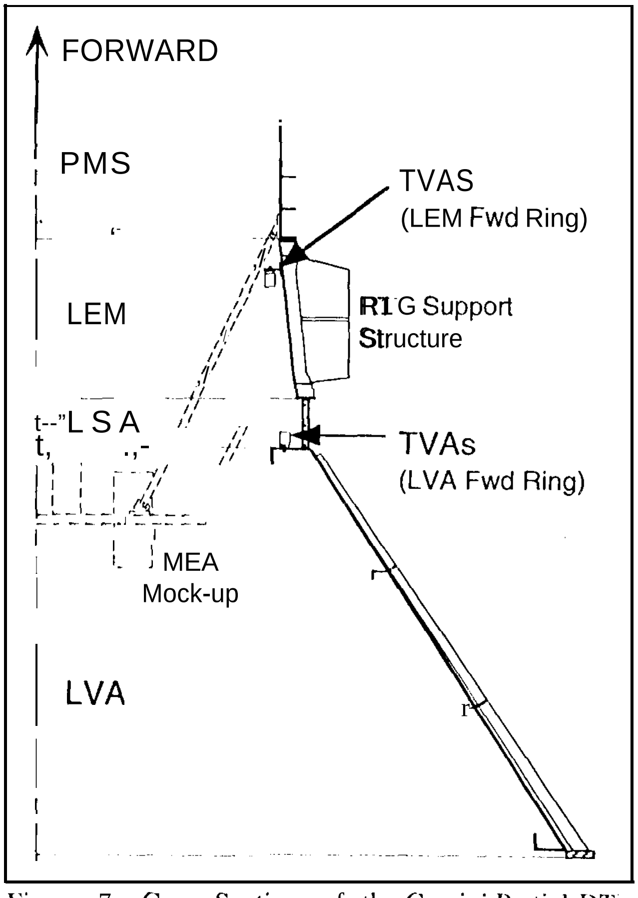


Figure 7: Cross Section of the Cassini Partial-DTM Showing Spacecraft-Axial Locations of TVAs.

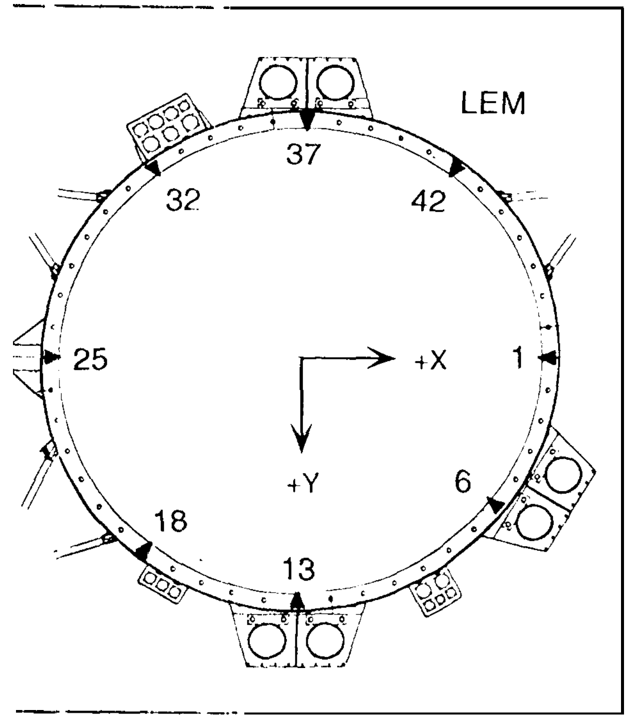


Figure 8: Cross Section of Cassini LEM (looking aft) Showing Circumferential Locations of TVAs.

To properly assess the performance of the TVAS, acoustic tests were performed on various configurations 01 the test article with and without the TVAs, however only the final configuration is addressed in this paper. Tests were performed at the Cassini Flight Acceptance (FA) acoustic levels shown in Figure 3 (143 dB OA) for a duration of one minute. All data was reduced to narrowband (5 Hz BW) power spectral density (PSD) levels.

TEST RESULTS

1 n addition to the acceleration measurements taken on the structure, several of' the TVAs were instrumented with accelerometers on the mass and base structure to verify their tuning during the tests. A typical TVA transmissibility is plotted in Figure 9 which shows expected TVA performance. The resonance peak at 200 Hz shows that the TVA was tuned properly. The amplification is roughly unity below the TVA resonance where the mass moves in phase with the structure. Around the TVA resonance (100-300 Hz), the amplified motion of the mass (Q≈4 in this case) cancels the vibration at the attachment point (see Figure 4). At higher frequencies, the TVA mass decouples from the structure as indicated by the roll-off in the transmissibility,

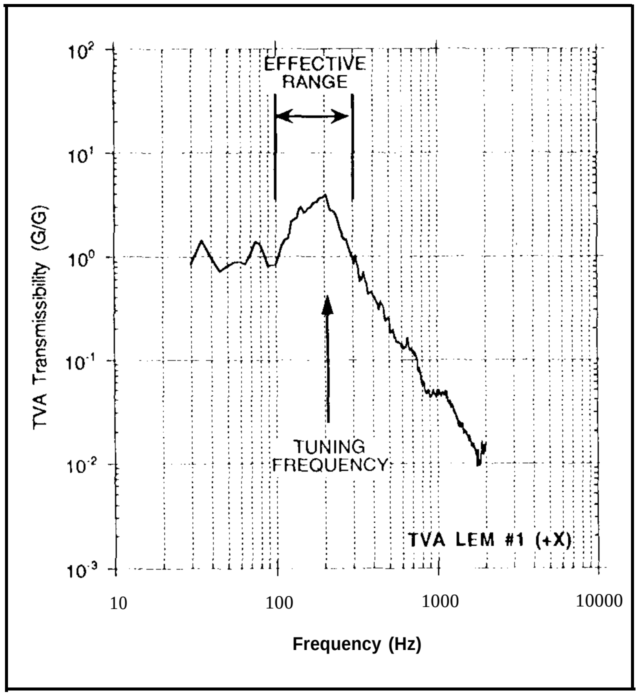


Figure 9: Typical TVA Transmissibility Measured During Partial-DTM Acoustic Test.

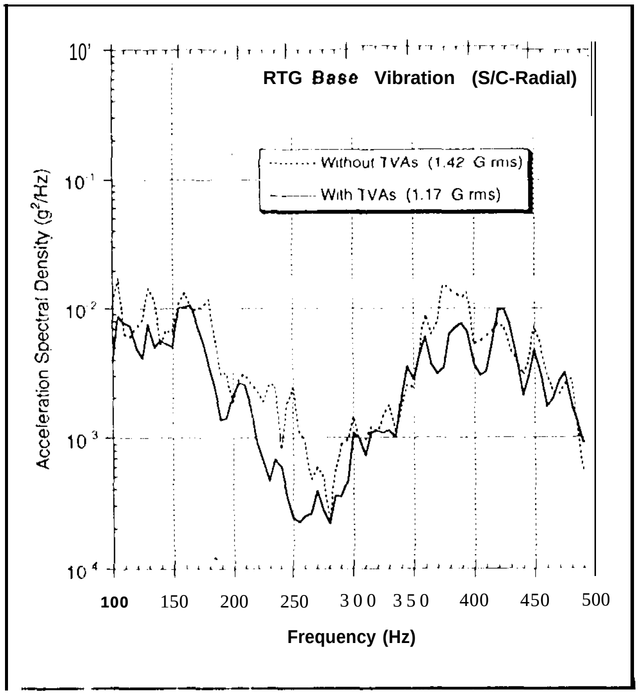


Figure 10: Radial Vibration Response of Structure at Base of the RTG Dynamic Simulator With and Without TVAS.

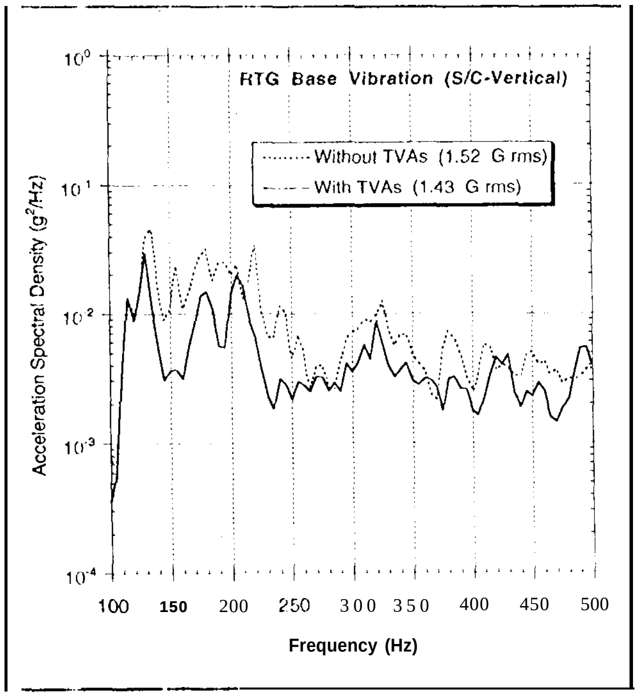


Figure 11: Vertical Vibration Response of Structure at Base of the RTG Dynamic Simulator With and Without TVAs.

Plots of the acceleration response at the base of the RTG dynamic simulator (at +Y support location), as an example, with and without the TVAs are given in Figures 10-12. The data from the two test runs were normalized to the same measured acoustic level. The reductions seen at the RTGs were consistent on the ring frames, RWAS, and MEA. The tests showed that about 3-6 dB reduction (varying with frequency) in spacecraft vibration around 200 Hz could be achieved for about 21.8 kg (48 lb) of TVA mass. In addition to the vibration reduction around the TVA resonance, attenuation is also observed at higher frequencies. This reduction may be due to additional damping provided by the VEM. Although the mass penalty is undesirable, it has been deemed acceptable.

CONCLUSIONS

The analyses and tests performed as part of the Cassini vibration damping investigation indicated that the acoustically induced structural vibration may be damped using TVAs. In addition, it was shown that attenuating the vibration of the primary structure helps to protect the attached hardware. Although it is usually desirable to consider damping early in the design, the add-on modification, which included flight-qualified materials, was effective with an acceptable mass impact. Additional

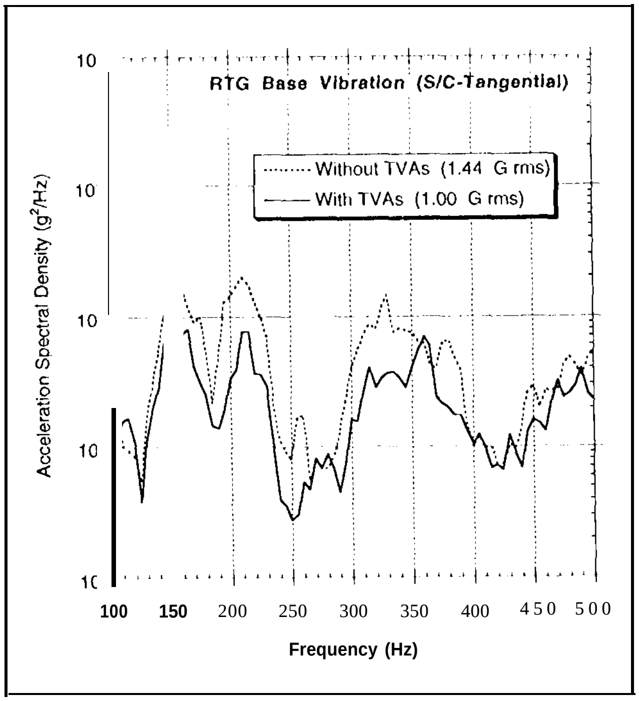


Figure 12: Tangential Vibration Response 01 Structure at Base of the RTG Dynamic Simulator With and Without TVAS.

studies arc in progress, in cooperation with NASA, Martin Marietta, and McDonnell Douglas, to assess the feasibility of mitigating the launch acoustic environment through modification of the PLF. The modifications involve upgrades to the acoustic blanketing on the PLF interior surfaces. Ultimately, the combination of the spacecraft and launch vehicle improvements arc expected to provide a reasonably benign vibroacoustic environment for Cassini at launch.

ACKNOWLEDGEMENTS

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